# Solar neutrino theory and open questions

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**Snowmass workshop – 07.12.20**

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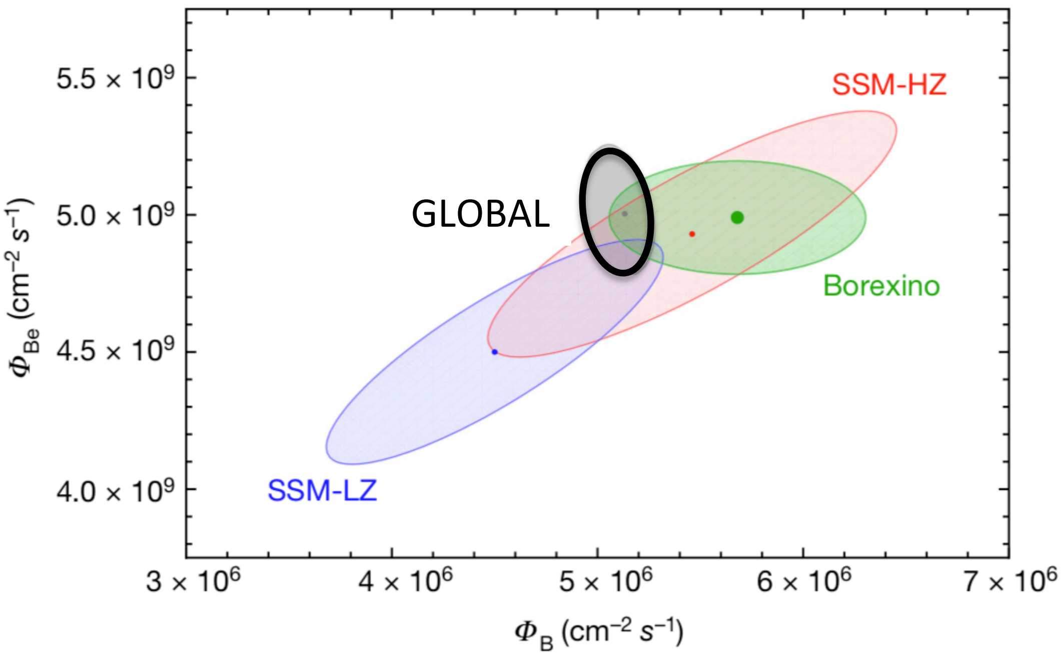
# Experimental status: pp-chains



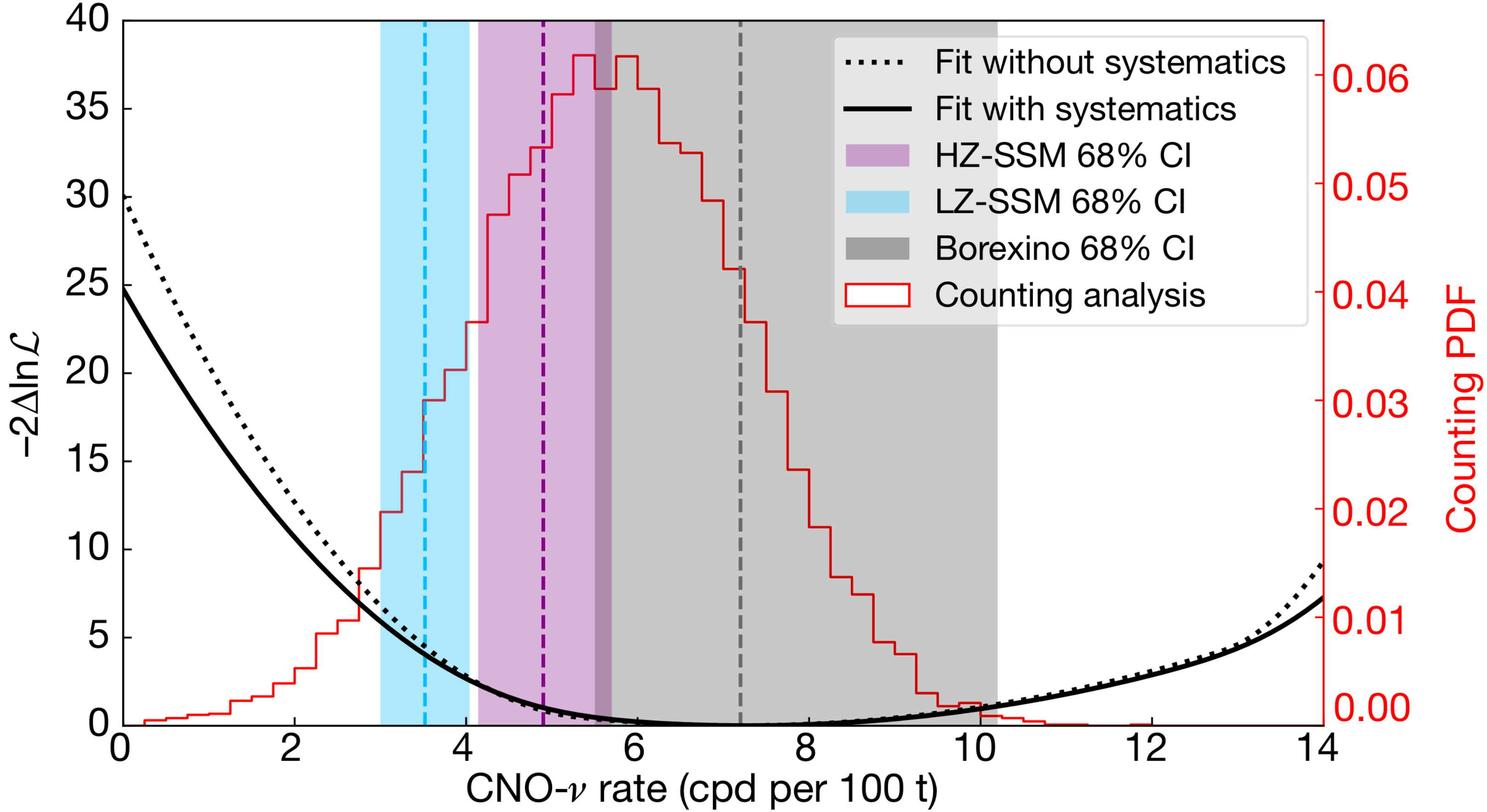

pp – 10% (Borexino, 2018)

pep – 10% (Borexino, 2018)

$^{8}$B – 2% (SNO+SuperK)

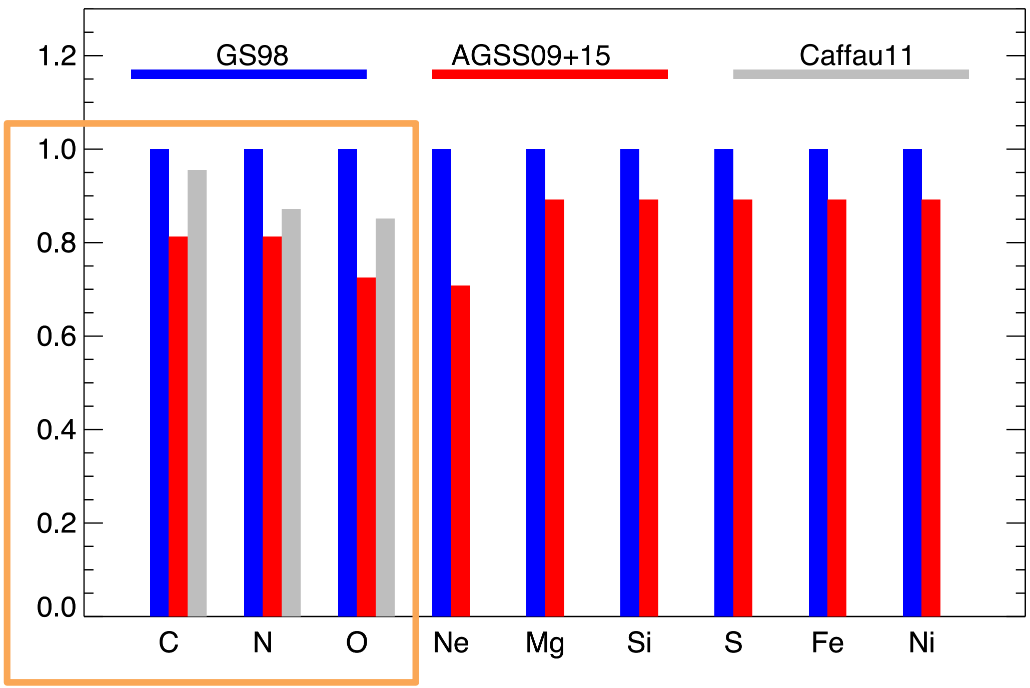
$^{7}$Be – 3% (Borexino)

# Experimental status: CN neutrinos



# Solar Composition

## Revision of solar abundances (Asplund et al., Caffau et al.)

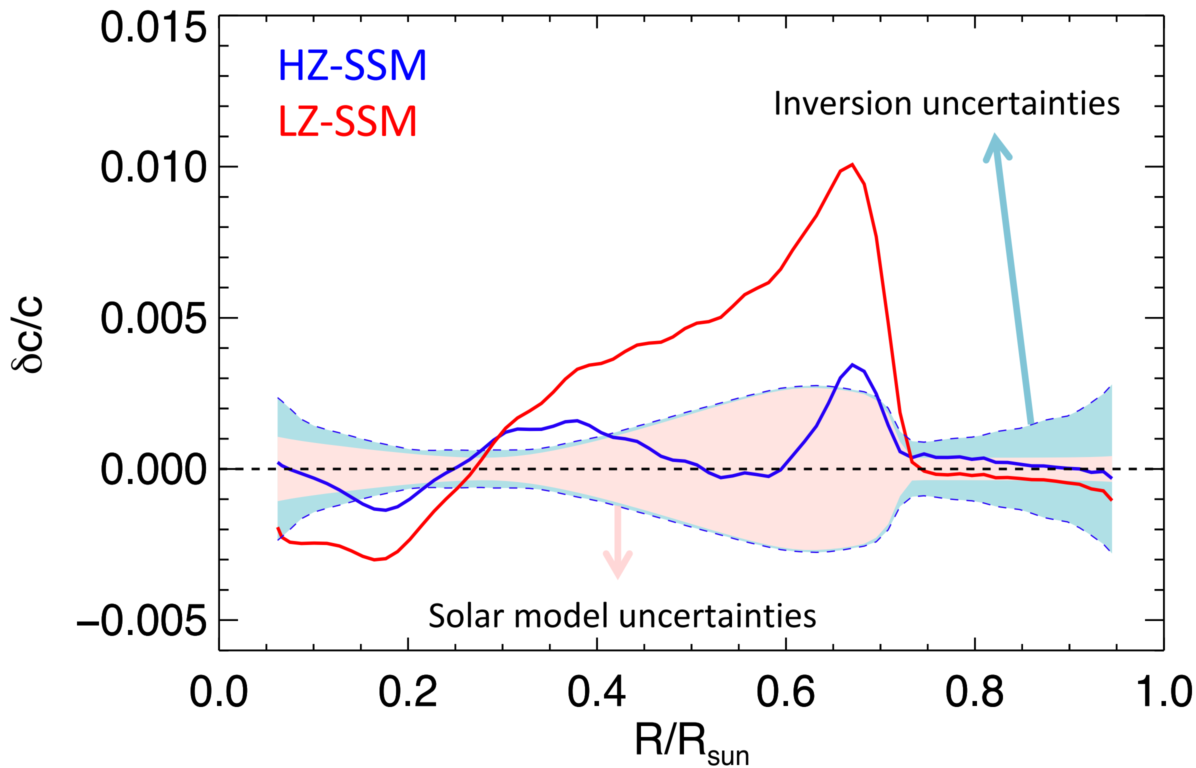



Large CNO reduction ~20-30%
Moderate refractories ~10%

~ half from 3D effects
~ half from atomic data, NLTE, blends

fundamental difference
between 3D groups related to
choice of lines
(good atomic data, blends)

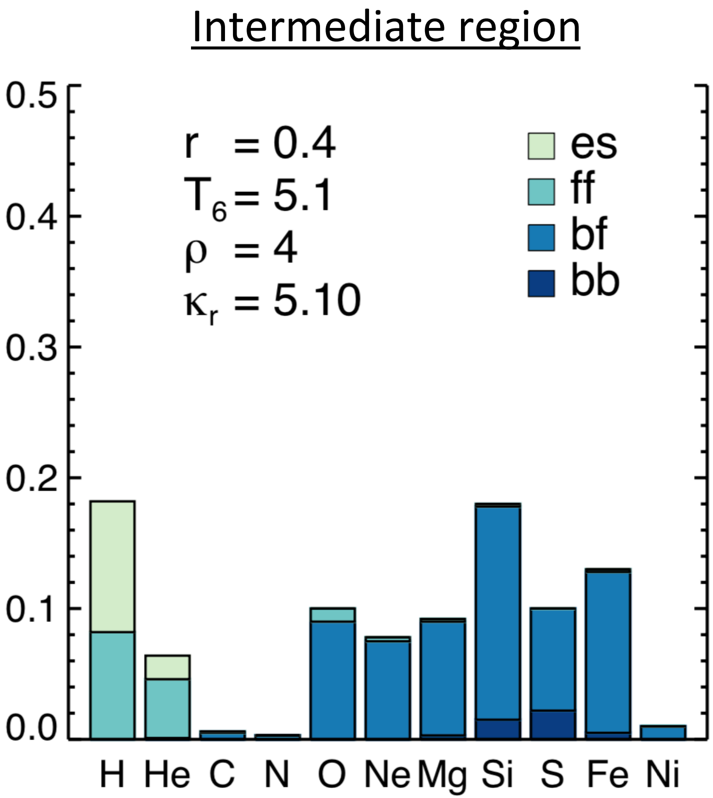
Solar modeling / abundances crisis after ↓ revision of solar abundances

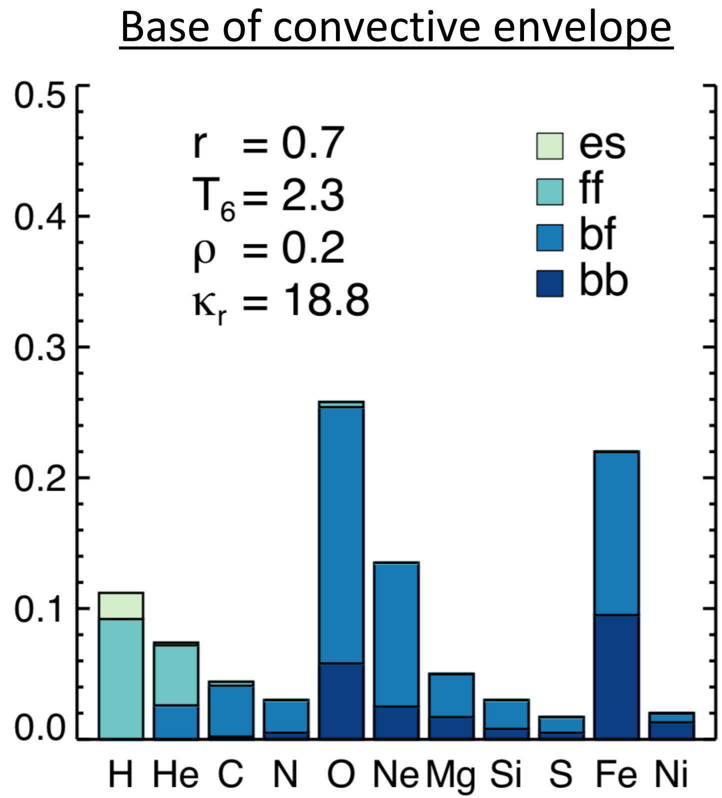



Sound speed inversions favor HZ-SSM

However, entropy inversions favor Z = 0.008 – 0.014 (even lower than LZ; Buldgen et al. 2017)

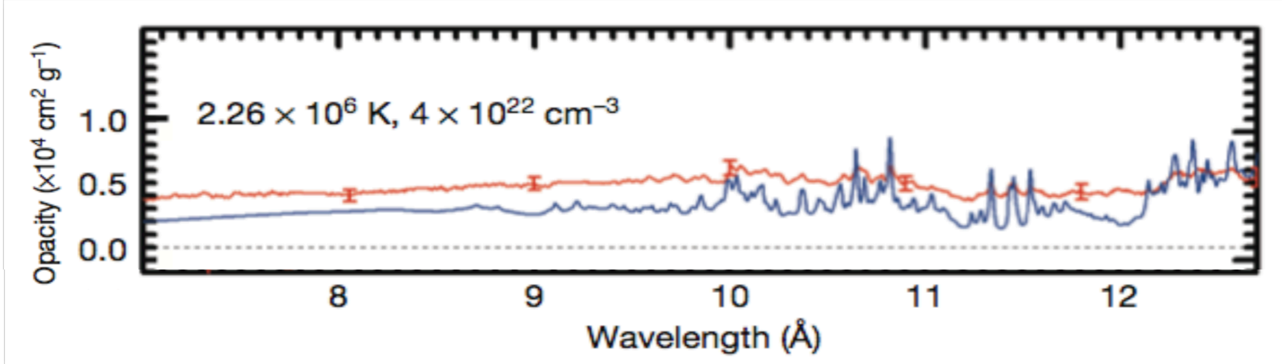
# Degeneracy composition - opacity



# Opacity – experimental state of the art

Fe opacity @Sandia Lab -- > 7% increase of Rosseland mean opacity (Bailey et al. 2015)




Missing quasi continuum opacity in models for Fe

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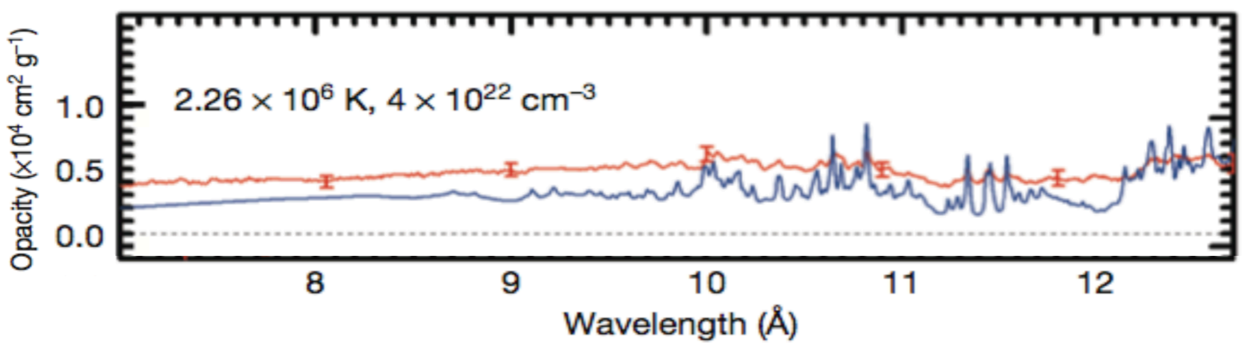



Missing quasi continuum opacity in models for Fe

Further experiments for Cr and Ni reveal (Nagayama et al. 2019):

- systematics for open L-shell configurations (Cr and Fe)
- line shape disagreement for all elements (problems with plasma interactions)

- but… quasi continuum opacity agrees for Cr and Ni → unknown T dependence or problems in Fe experiment

# Heavy elements – state of the art

Helioseismology:

HZ preferred by sound speed inversions, depth of convective envelope

LZ preferred by entropy inversions

Opacity experiments:

point towards deficient opacity calculations but Fe results not fully understood

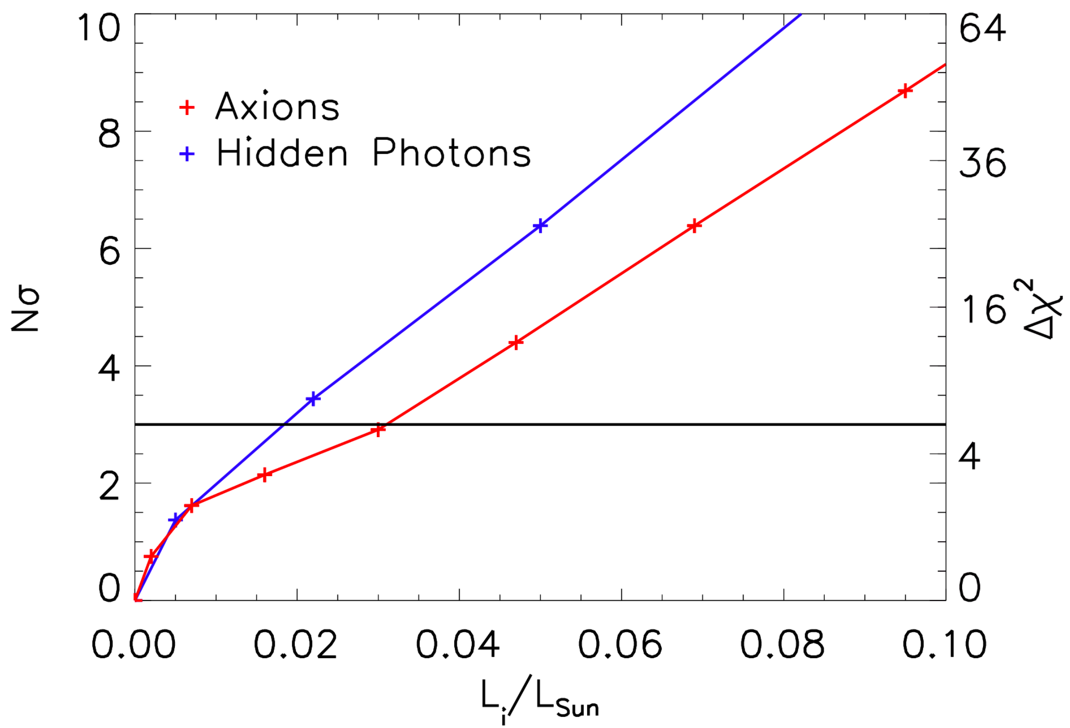
Spectroscopic determinations:

new work ongoing (Bergemann et al.): new model atmospheres (including chromosphere), NLTE modeling of Ni (blended line with O) and new atomic O data (new model atom for NLTE). Future revision of C & N planned.

CN measurement by ν-experiments independent check on C(+N) < 10%

# Solar luminosity

Combination of helioseismic + neutrino constraints (model dependent)
exclude other channels at 3% (3-σ)



# Solar luminosity

Following Borexino 2018:

$$L_{\rm exp} = \left(3.89^{+0.35}_{-0.42}\right) \times 10^{33} {\rm erg/s} = \left(1.01^{+0.09}_{-0.11}\right) {\rm L}_\odot$$

pp measurement at 1% (1-σ) would yield comparable constraints (model indepdent)

# Summary – wish list

- pp measurement at 1% (1-σ) would yield comparable constraints (model indepdent)
- CN measurement < 10%
  - solar abundance problem
  - but C+N abundance for solar physics in general:
    test on solar models, e.g. mixing
    initial (in)homogeneity, e.g. accretion of protoplanetary disk w/different composition